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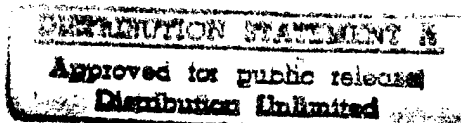
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Electronic Applications of Magnetic Resonance Force Microscopy

Progress Report
ONR Contract N00014-95-C-0124

July 1996

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Much of the focus of the last year has been on improving the basic technology of magnetic resonance force microscopy (MRFM) and working towards the dual goals of dopant imaging and single electron spin detection. Recent accomplishments are described below.

MRFM detection and spectroscopy of phosphorus dopants in silicon¹

One of the key goals outlined in our contract proposal was to demonstrate that MRFM could indeed detect dopants in silicon. This has been accomplished for the case of phosphorus (n-type) dopants using a low temperature MRFM apparatus. For a sample with moderate doping density ($4 \times 10^{18} \text{ cm}^{-3}$), the magnetic resonance force microscope detected a single strong electron spin resonance (ESR) spectral line. For a lower density sample ($8 \times 10^{16} \text{ cm}^{-3}$), the ESR spectrum was observed to consist of two lines separated by 42 gauss. These results are in accord with our expectations since it is known that the donor electrons in the higher concentration sample exist as delocalized conduction electrons, even at low temperatures. In contrast, the donor electrons in the lower concentration sample will "freeze out" at low temperature and be localized to the sites of the phosphorus atoms. The ESR spectrum for the localized electrons is then split by hyperfine coupling to the spin 1/2 phosphorus nuclei. These results are significant for two reasons: 1) they show that MRFM can indeed detect n-type dopants as required for future dopant profiling studies, and 2) they represent the first example of MRFM spectroscopy. Further details may be found in the attached manuscript² entitled "Magnetic resonance force detection and spectroscopy of electron spins in phosphorus-doped silicon".

Adiabatic Inversion, Nutations and Spin Echoes of Electron Spins in SiO_2

Electron spin resonance in amorphous SiO_2 was studied by MRFM in order to gauge the suitability of this material as a test sample for future single spin experiments. Gamma irradiation was used to create point defects consisting of dangling sp^3 orbitals (E' centers). MRFM experiments performed at 5K verified the desirable long relaxation time of the material (~ 3 seconds). The experiments also showed that the technique of cyclic adiabatic inversion could be used to generate the oscillatory force signal needed to drive the vibration of the cantilever. The ability to manipulate the spins and detect their response was confirmed in experiments that demonstrated coherent nutation and spin echoes. The detection of spin echoes is especially significant because it is the basis of many conventional magnetic resonance techniques and shows that conventional spin manipulation methods can be combined with MRFM detection. Details of this work can be found in the attached preliminary manuscript³ entitled "Force-detected Electron Spin Resonance: Adiabatic Inversion, Nutation and Spin Echo".

Development of Ultrasensitive Cantilevers

One of the keys to single spin detection by MRFM is the development of ultrasensitive micromechanical force sensors. Working in collaboration with Prof. Tom Kenny's group at Stanford University, single crystal silicon cantilevers were developed that are capable of detecting forces as small 10^{-17} Newtons. (For reference, conventional atomic force microscopes usually detect much larger forces, in the range of 10^{-9} - 10^{-12} Newtons.) Figure 1 shows a typical cantilever with an in-plane magnetic tip. Spring constants below 10^{-5} N/m were obtained in cantilevers as thin as 50 nm. The in-plane geometry was designed to be compatible with the vertical cantilever

orientation shown in Fig. 2. The vertical orientation allows the very soft cantilever to approach to within 10 nm of the surface without being "snapped" into the surface by van der Waals forces. Details of the cantilever fabrication and testing may be found in the attached manuscript⁴ entitled "Ultrasensitive Vertical Force Probe for Magnetic Resonance Force Microscopy".

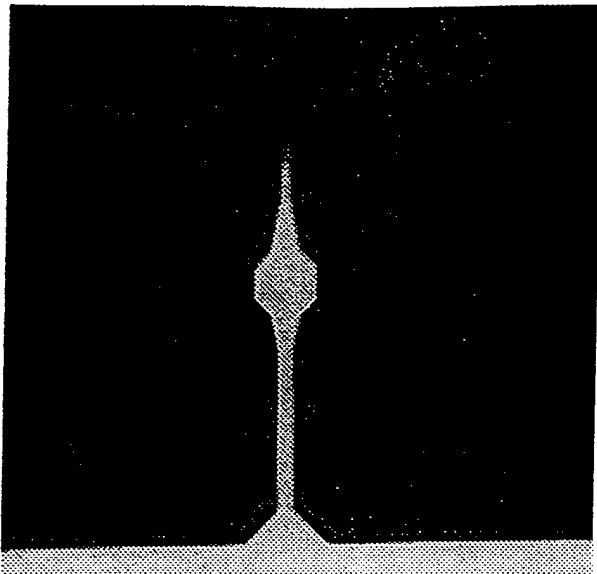
Instrumentation Upgrades and Testing

Two low temperature MRFM apparatuses are undergoing tests. One apparatus is designed for single spin detection and is optimized for small scan area (<100 nm) and extreme force sensitivity. Using a 50 nm thick single crystal silicon cantilever, this apparatus has achieved a force sensitivity of 10^{-17} N at 4K. This sensitivity should be sufficient to detect the force from individual electron spins. The second apparatus is a general purpose MRFM apparatus and is being adapted for larger scan size (>50 μ m) as required for dopant profile studies. Experiments on three-dimensional dopant imaging and single spin detection will commence in the near future.

References

- ¹ Most of the dopant detection work was performed at IBM expense after the submission of our contract proposal but before the ONR contract was finalized. We include it as part of this progress report because it is so intimately tied to the goals of the contract.
- ² K. Wago, O. Zuger, J. Wegener, R. Kendrick, C.S. Yannoni and D. Rugar, "Magnetic Resonance Force Detection and Spectroscopy of Electron Spins in Phosphorus-doped Silicon", submitted to J. Appl. Phys.
- ³ K. Wago, D. Botkin, O. Zuger, R. Kendrick, C.S. Yannoni and D. Rugar, "Force-detected Electron Spin Resonance: Adiabatic Inversion, Nutation and Spin Echo", unpublished manuscript.
- ⁴ T. Stowe, K. Yasumura, T. Kenny, D. Botkin, K. Wago and D. Rugar, "Ultrasensitive Vertical Force Probe for Magnetic Resonance Force Microscopy", Proceedings of the 1996 Solid State Sensors and Actuators Workshop, pp. 225-230.

Single crystal silicon "spearhead"



Thickness = 500 - 1700 Å
 $k = 10^{-6} - 10^{-3}$ N/m
 $Q = 28,000$ at 5K

Figure 1 - Ultrathin single crystal silicon cantilever capable of detecting forces as small as 10^{-17} N. Cantilever includes an in-plane tip with radius of curvature below 50 nm. A thin magnetic layer is deposited on the tip to make it spin sensitive. Cantilever produced in collaboration with Prof. T. Kenny, Stanford University.

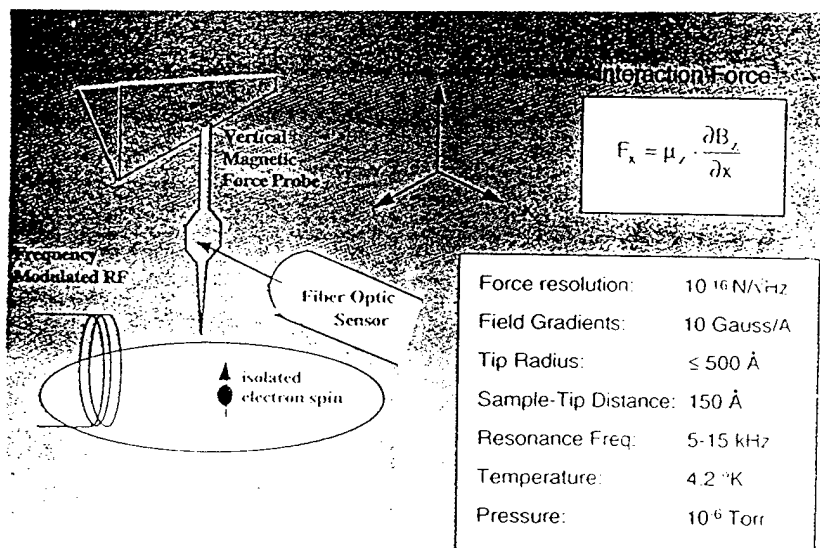


Figure 2 - Vertical cantilever orientation chosen for the single spin detection experiment allows the ultrathin cantilever to approach surface of sample without "snap in".